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# (54) Laser beam converter

(57) A laser beam with non uniform intensity profile is given a uniform intensity profile by passage through a principal focusing lens and a phase zone plate array having a random two dimensional array of close packed diffracting Fresnel type zone plates 17, 19 and modified by having the radii of the concentric annuli proportional to the square root of whole numbers and the spaces between the annuli alternatively arranged to cause a phase delay of 0 or π radians. Half of the plates have a central zone 16 of 0 radius phase delay and the other half a central zone 18 of π radius phase delay. The focal length of the zone plates, which can be circular or elliptical, may be varied at random across the phase zone plate array. For use in laser fusion, heat treatment, plasma interactions, or generation of X-rays the phase zone plate array is placed either before or after the principle focusing lens and this combination is placed between the laser source and a target which, to achieve a uniform focal spot profile intensity, is placed slightly out of focus.

Fig.4.

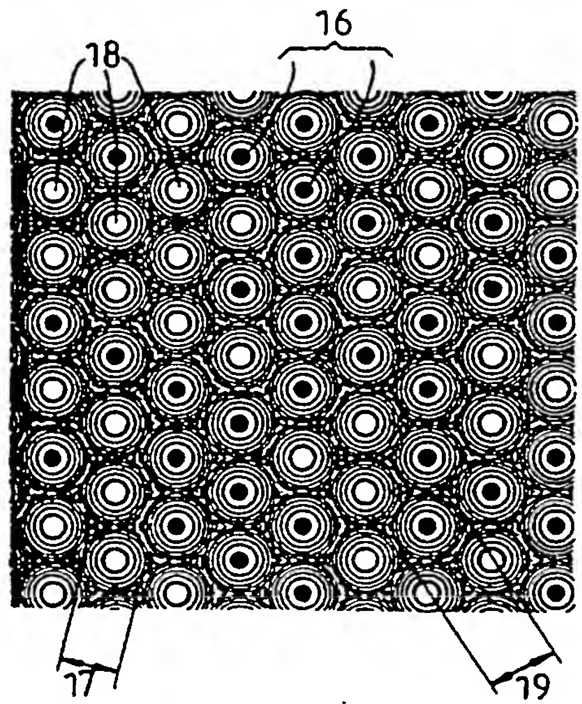


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Fig.4.

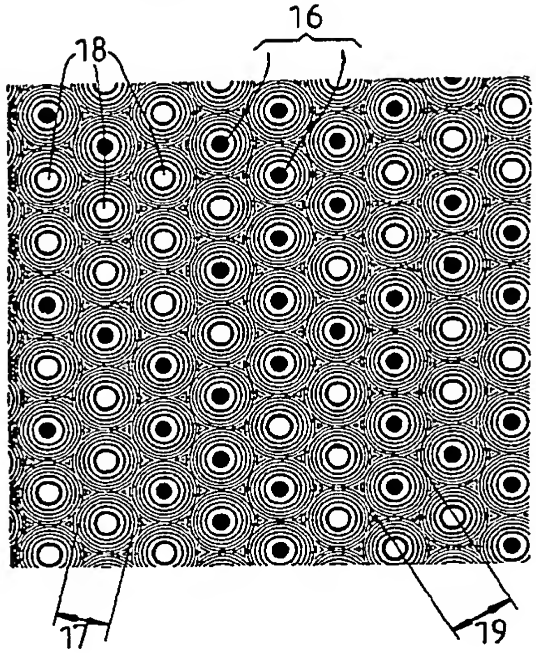
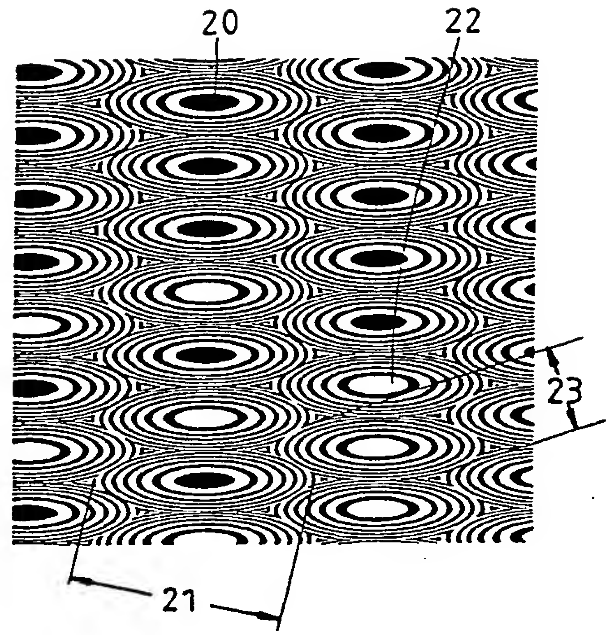



Fig.5.



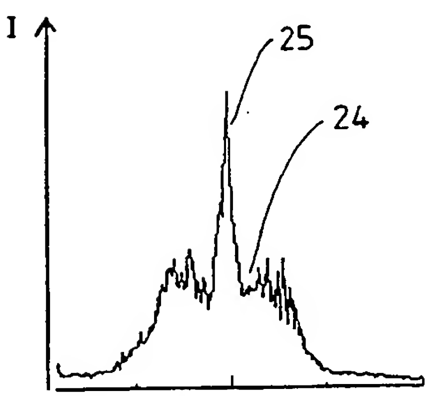




Fig.6.

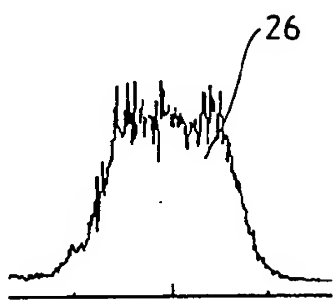



Fig.7.

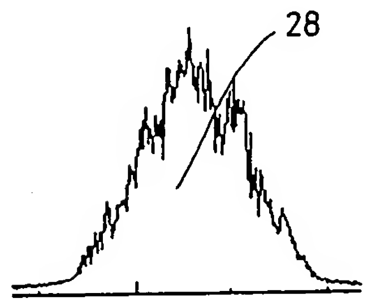
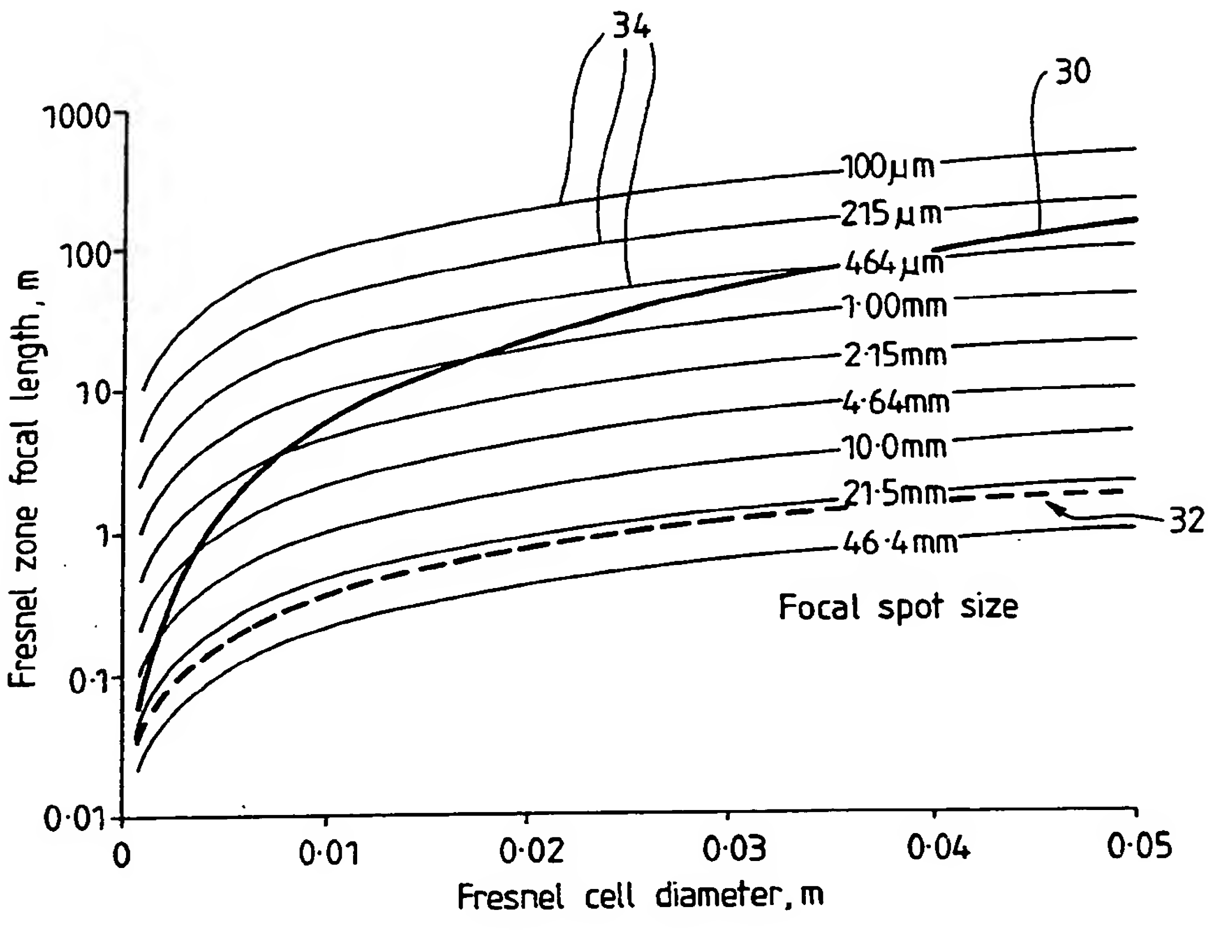



Fig.8.

Fig.9.


34
30
1000
100
10
1
0·1
0·01
Fresnel zone focal length, m
100µm
215µm
464µm
1·00mm
2·15mm
4·64mm
10·0mm
21·5mm
46·4mm
32
Focal spot size
0
0·01
0·02
0·03
0·04
0·05
Fresnel cell diameter, m

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LASER BEAM CONVERTER

The present invention relates to laser beam converters for the conversion of laser beams with non uniform intensity profiles into laser beams with uniform intensity profiles.

The invention is suitable for lasers with wave lengths in the range near infra red to near ultra violet, and with powers in the range milliwatts to terrawatts.

Laser beam converters are of considerable importance in many manufacturing processes. A continual problem with laser beams for a number of applications such as laser fusion, laser heat processing, laser beam plasma interactions and generation of X-rays by laser illumination is the poor quality of the laser beam with respect to the variable intensity across the beam at the point of interaction between the laser and the area chosen to be illuminated. This area is sometimes referred to as the target spot.

Efficiency is, in general, improved by using a beam with a uniform intensity at the target spot. The ideal intensity profile at the target spot is one with a flat top.

It is therefore common practice to use a laser beam converter to improve energy transfer between the laser and the target.

It is an object of the current invention to overcome the inefficiencies of current techniques of producing high quality laser beams with uniform intensity profiles by use of a converter consisting of an array of binary phase zone plates in a focusing system to provide a laser beam with a non-uniform intensity profile.

A typical form of a laser beam converter is described in: Kato et al. Phys. Rev. Letters No.53 p1057 (1984).

The Kato converter consists of a random phase plate placed between a laser source and a focusing lens. The random phase plate consists of a two dimensional array of areas each of which applies a phase delay randomly chosen to be either 0 or $\pi$ radians. The areas in the Kato phase plate are arranged in a interlocking pattern of two types of squares causing or not causing a phase delay. The laser beam is diffracted by the edges of the squares, and overlap at the target spot.

Another form of laser beam converter is described in: Deng et al. Appl. Optics Vol.25. No.3 p377 (1986). The Deng converter consists of an array of nearly 100 similar small lenslets placed ahead of a principal focussing lens in a laser beam path. The array of lenslets splits the laser beam into many partial beams which are focused to overlap at the target spot. The intensity non-uniformity of the incident beam is greatly reduced, and an approximately flat top intensity profile is obtained.

According to the present invention a laser beam converter includes a phase zone plate and a principal focusing lens, the phase zone plate consisting of a random two dimensional array of close packed diffracting zone plates each of which consists of a zone plate pattern of concentric annulii with radii proportional to the square root of whole numbers with the annular space between the annulii forming zones alternately arranged to cause a phase delay of 0 or $\pi$ radians wherein substantially one half of the zone plates have a central zone of 0 radians phase delay and substantially the other half having a central zone of $\pi$ radians phase delay.

The current invention overcomes the disadvantages of the known techniques by providing a number of binary phase zone plates in an array her in conveniently referred to as a Phase Zone Plate (PZP) for

the generation of a range of focal profiles to produce relatively flat top intensity distributions from a non-uniform input beam. The invention uses a PZP and a principal focusing lens. The design of each zone plate in the PZP array is based on the well known Fresnel zone plate.

As with the Fresnel zone plate the zones of the individual zone plates in the PZP array are the annular spaces between adjacent annulii whether arranged in a pattern of concentric circles, or ellipses or distorted circles. It is an important disclosure of the invention that alternate zones within each individual zone plate cause either a 0 or $\pi$ radian phase delay to the laser beam passing through the PZP. Furthermore the PZP includes two types of individual zone plate each present in equal quantities but differing according to whether the central zone causes a 0 or $\pi$ radian phase delay. The distribution of each type of zone plate is random across the PZP.

Thus the PZP consists of a two dimensional array of areas each of which applies a phase delay randomly chosen to be either 0 or $\pi$ radians and the areas of 0 and $\pi$ radians delay are present in equal quantities and randomly distributed within the overall pattern. The effect is to scramble the delayed and undelayed regions.

The PZP can be placed either side of the principal focusing lens. A target plane is positioned at but preferably slightly behind the focal plane of the principal focusing lens (that is further away from the laser source).

A PZP plate according to the invention is fabricated using conventional photo-lithographic techniques to give phase delays of 0 or $\pi$ radians in the even or odd orders of zones in the individual zone plates.

Application of a photo-resistive transparent coating to a glass substrate is well known, but the current invention discloses applying a transparent coating to the substrate of a thickness that will cause a phase delay of $\pi$ radians and then etching local areas of the coating to leave only the glass or other suitable substrate which will cause a phase delay of 0 radians.

The PZP manufacturing process requires three main elements:

(i) A transparent mask with the PZP design is made by printing on to an acetate film with the 0 and $\pi$ radians phase delay areas respectively transparent and opaque;

(ii) A chrome plated quartz slide overcoated with a visible light photo resist, this is a commercially available product;

(ii) A glass substrate coated with a ultra-violet (UV) photo-resist to the required thickness with the UV photo-resist spin coated onto the substrate and the thickness controlled by varying either the spin speed or the concentration of the UV photo-resist, and fixed by baking in an oven at 160 degrees centigrade for 20 minutes.

The manufacturing process commences with an exposure of the visible light photo-resist through the acetate mask. The visible light photo-resist is then developed to remove any exposed areas, and the slide further processed in a chrome etch solution to remove the now unprotected chrome. All the remaining visible light photo resist is removed by a further exposure and development, resulting in a positive image master plate. This is then used to mask the exposure of the UV photo-resist. When the plate is developed it leaves the substrate with the unexposed UV photo-resist as the final optical element that forms the PZP.

To obtain satisfactory focal spot profiles the resist thickness must not vary by more than 1%. If the thickness is outside this tolerance a coherent spike is produced in the centre of the spot profile. This tolerance is un-realistic with the manufacturing technique described above. It is possible, however, by placing the target slightly out of the focal plane to widen the permitted thickness tolerance. An optimum defocusing distance has been calculated to be:

$$W = \frac{0.1\,(f_p - d)^2}{f_p - d + f_z}$$

where:

W is the defocusing distance behind the focal plane of the principal focusing lens

fp is the focal length of the principal focusing lens

fz is the nominal focal length of individual zone plate and

d is the distance between the PZP and the principal focusing lens.

At this plane (W behind the focal plane of the principal focussing lens) no significant increase in overall size of the focal spot occurs, but the coherent central spike will be defocused to approximately half the size of the spot profile. This degree of defocusing is possible due to the large depth of focus from the elements of the PZP compared to the depth of focus of the coherent spike.

A PZP according to the invention is substantially transparent to light.

The thickness of the n delayed areas and therefore the thickness of the UV photo-resistive layer is given by:

$$t = \frac{\lambda}{2(n-1)}$$

where:

t is thickness to give n phase delay

$\lambda$ is wave length

n is refractive index of the UV photo resist

Alternatively with known techniques it is possible to etch into the surface of the glass to give the same effect.

In preferred form of the invention the focal lengths of the diffracting zone plates are varied at random across the PZP within the range plus or minus 1% to plus or minus 10%. It is a well known application of a Fresnel zone plate that it performs a function similar to that of a lens and it will be understood that each individual pattern of circles, or ellipses, or distorted circles, conveniently referred to as zone plates will have a focal length analogous to that of a lens. It is an important part of the disclosure of the current invention that the focal lengths of each zone plate in the array on the PZP vary at random by a chosen figure. It will be understood by those skilled in the art that variations in the focal lengths in theory by upto plus or minus 10% are possible whilst still maintaining a uniform spot intensity profile. In the examples provided below a random variation of plus or minus 1% has been demonstrated to be effective and that the diameters of the central zones were varied to achieve this variation.

The nominal focal length of a zone plate is given by:

$$f = \frac{R_m^2}{m\lambda}$$

where:

$R_m$ is the radius of the mth zone; and

$\lambda$ is the wave length

In practice the focal lengths of the zone plates are varied by imposing a variation chosen from the range plus or minus 1% to plus or minus 3% on the diameter of the central zone.

The combination of the PZP and principal focussing lens gives a resultant focal spot size at the calculated according to:

$$W_s = W_z F_p \Big/ \left( R_m^2/m\lambda - \frac{m\lambda}{4} \right)$$

where:

$W_s$ is focal spot size

$W_z$ is the diameter of the individual Fresnel zones

$F_p$ is the focal length of the principal lens

$R_m$ the radius of the Fresnel zone of order m and

$\lambda$ the wavelength of light.

In another form of the invention the PZP consists of plurality of diffracting zone plates stacked together so that the centres of any three adjacent diffracting cells are situated at the corners of a triangle to achieve a closed packed structure of the zone plates in the PZP.

In yet another form of the invention the PZP consists of plurality of diffracting zone plates stacked together so that the centres of any four adjacent diffracting zone plates are situated at the corners of a square or rectangle.

Preferably, the PZP consists of a plurality of diffracting zone plates in which the annulii are circular.

In another form of the invention the PZP consists of a plurality of diffracting zone plates in which the rings are elliptical.

In yet another form of the invention the PZP consists of a plurality of diffracting zone plates in which the annulii are distorted circles such as ovoids.

Preferably the zones of the PZP are causing a 0 or $\pi$ radians phase delay are substantially equal in area.

Preferably there is a minimum of four zones within one diffracting zone plate.

Preferably there the minimum structure that can be resolved within a diffracting zone plate is greater than 40 $\mu$m.

In a preferred embodiment of the invention the PZP can be placed either before or after the principal focusing lens and this lens combination is placed between the laser source and a target placed slightly behind the focal of the principal focusing lens to achieve a substantially uniform focal spot profile intensity.

Some embodiments of the invention will now be described, by way of example only, with reference to the accompanying diagrammatic drawings of which:

Fig. 1 is a schematic arrangement of a converter according to the invention;

Fig. 2 is a representation of the beam intensity before passing through a converter according to the invention;

Fig. 3 is a representation of the beam intensity after passing through a converter according to the invention;

Fig. 4 is a plan view of a first PZP mask for generating a binary phase zone plate array according to the invention;

Fig. 5 is a plan view of second PZP mask for generating a binary phase zone plate array according to the invention;

Fig. 6, 7 and 8 are focal spot profiles obtainable by the use of the invention; and

Fig. 9 is a family of graphs showing the range of focal spot sizes obtainable using the invention.

A laser beam converter according to the invention (Fig. 1) has a laser source 2 focussed on a target 8. A principal focussing lens 4 lies between the target 8 and the the laser source 2. A PZP with a binary phase zone plate array 6 lies between the principal lens 4 and the target 8. The target spot 10 is the region of interaction between the focused laser beam and the target 8.

The curve 12 of intensity of the laser beam against distance across the target spot 10 is shown at Fig 2 for systems without a laser beam converter.

The curve 14 of intensity of the laser beam against distance across the target spot 10 is shown at Fig 3 for systems with a laser beam converter according to the invention.

Fig.4 shows a PZP mask design printed on a transparent acetate sheet for generation of the phase distributions of a binary phase zone plate (PZP). The design consists of a random two dimensional array two types of hexagonally close packed zone plates 17 and 19. each of which consists of a pattern of concentric rings with radii proportional to the square root of whole

numbers with the annular spaces between the rings forming zones which are alternately rendered opaque to light and shown black in Fig. 4. The black central zones 16 and white central zones 18 represent 0 or $\pi$ phase delays respectively in the PZP. The zone plates 17 and 19 are randomly distributed across the PZP mask to minimise any zeroth order coherence spike, and equal numbers of black central zones 16 and white central zones 18 are present. The zone plates 17 and 19 are circular and include a minimum of four zones alternately black and white to produce 0 or $\pi$ phase delays in the PZP. The mask in Fig.4 generates a PZP that in turn produces a circularly symmetric target spot 10. In addition the central zones 16 and 18 vary randomly in diameter by plus or minus 1%.

Fig. 5 shows a PZP mask design printed on a transparent acetate sheet for generation of the phase distributions of a binary phase zone plate array (PZP). The design consists of a random two dimensional array two types of hexagonally close packed zone plates 21 and 23 each of which consists of a pattern of concentric ellipses with major and minor radii proportional to the square root of whole numbers with the annular spaces between the ellipses forming zones which are alternately rendered opaque to light and shown black in Fig. 5. The black central zones 20 and white central zones 22 represent 0 or $\pi$ phase delays respectively in the PZP. The zone plates 20 and 21 are randomly distributed across the PZP mask to minimise any zeroth order coherence spike, and equal numbers of black central zones 20 and white central zones 22 are present. The zone plates 21 and 23 are elliptical with, in this example, a major to minor diameter ratio of 3:1 and include a minimum of four zones alternately black and white to produce 0 or $\pi$ phase delays in the PZP. The mask in Fig. 5 generates a PZP that in turn produces a shaped focal profile with a 3:1

aspect ratio. In addition the major and minor diameters of central zones 20 vary randomly in diameter by plus or minus 1% whilst keeping the 3:1 aspect ratio. Similarly the major and minor diameters of central zones 22 vary randomly in diameter by plus or minus 1% whilst keeping the 3:1 aspect ratio.

The mask type shown in Fig. 4 with zones 17 and 19 of nominal 20 mm diameter and 17 m focal length when used with a 200 mm principal focusing lens and with a 0.527 μm laser beam produces a 235 μm spot in the far-field.

A line scan 24 of the focal spot in the focal plane of the principal lens 4 is shown in Fig.6. A central spike 25 is clearly present, but if the target plane is moved slightly beyond focus to the position 9 in Fig 1 the central spike can be defocused relative to the spot. The far-field image in a plane 300 μm after focus position 9 is shown in Fig. 7. In this plane there is still a relatively flat topped focal spot profile 26 with a slight degradation in the edge definition. If the lens is further defocused to position 11 in Fig. 1 the spot profile 28 becomes more gaussian Fig. 8

The range of focal spots 10 that can be generated using this technique is limited by: the focal length 7 of the principal focusing element; the size of the smallest structure within the zone plates 17, 19, 21 or 23 of the PZP which can be manufactured using a photo-lithographic process; and that the zone plates 17, 19, 21 or 23 must contain at least four zones.

The graphs 34 in Fig.9 demonstrates the range of focal spot sizes 10 available for a 1 m focal length lens at 1.053 μm. The two boundary conditions between which the PZP masks can be manufactured using current techniques, although this is not an absolute limit, are given by the heavy lines 30 and 32. The solid line 30 is

where each zone plate has only four zones, and the dotted line 32 is where the minimum structure size within the zone plate that can be resolved by current manufacturing techniques is 40 $\mu m$. The thin lines 34 on the graph are lines of constant focal spot size 10, calculated from the zone plate diameters 17 or 19 and the focal length 5 of the zone plates.

The graphs in Fig 9 can also be used with focal lengths other than 1 m, and with different wavelengths. This is achieved by scaling the focal spot sizes 10 by the focal length of the principal lens in metres and by the ratio the used wavelength to 1.053 $\mu m$.

The uniform intensities obtained from converters according to the invention are a result of the overlapping images produced by de-focusing the principal focusing lens PZP combination. Due to the averaging of many beamlets this technique is largely independent of the cross-sectional geometry of the input beam.

Converters according to the invention produce laser beams with a range of focal profiles with a more uniform, flat topped spot. These beams have been used in laser-plasma interaction experiments and also have been used to generate uniform X-ray profiles by illumination of gold targets with a converted laser beam.

WHAT IS CLAIMED IS:

1. A laser beam converter including a phase zone plate array and a principal focusing lens, the phase zone plate array consisting of a random two dimensional array of close packed diffracting zone plates each of which consists of a zone plate pattern of concentric annulii with radii proportional to the square root of whole numbers with the annular space between the annulii forming zones alternately arranged to cause a phase delay of 0 or n radians wherein substantially one half of the zone plates having a central zone of 0 radians phase delay and substantially the other half having a central zone of n radians phase delay.

2. A laser beam converter as claimed in Claim 1 characterised in that the focal lengths of the diffracting zone plates are varied at random across the phase zone plate within the range plus or minus 1% to plus or minus 10% and that the diameters of the central zones are varied to achieve this aim.

3. A laser beam converter as claimed in Claim 1 and Claim 2 characterised in having a phase zone plate with a plurality of diffracting zone plates packed together so that the centres of any three adjacent diffracting zone plates are situated at the corners of a triangle.

4. A laser beam converter as claimed in Claim 1 and Claim 2 characterised in having a phase zone plate with a plurality of diffracting zone plates packed together so that the centres of any four adjacent diffracting zone plates are situated at the corners of a square or rectangle.

5. A laser beam converter as claimed in Claim 1 and Claim 2 characterised in having a phase zone plate with a plurality of diffracting zone plates packed together so that the centres of any six adjacent diffracting zone plates are situated at the corners of a hexagon.

6. A laser beam converter as claimed in any one of Claims 1 to 5 characterised in having a phase zone plate with a plurality of diffracting zone plates in which the annulii are circular.

7. A laser beam converter as claimed in any one of Claims 1 to 5 characterised in having a phase zone plate with a plurality of diffracting zone plates in which the annulii are elliptical.

8. A laser beam converter as claimed in any one of Claims 1 to 5 characterised in having a phase zone plate with a plurality of diffracting zone plates in which the annulii are distorted circles.

9. A laser beam converter as claimed in any one of claims 1 to 8 characterised in that the zones causing a 0 or π radian phase delay are substantially equal in area.

10. A laser beam converter as claimed in any one of Claims 1 to 9 characterised in that there is a minimum of four zones within one diffracting zone plate.

11. A laser beam converter as claimed in any one of Claims 1 to 10 characterised in that the minimum structure size within the diffracting zone plate is about forty um.

12. An apparatus comprising a laser beam converter as claimed in any one of the Claims 1 to 11 adapted so that in use the phase zone plate array can be placed either before or after the principal focusing lens and that this combination is placed between the laser source and a target at the focal plane of the principal focusing lens to achieve a substantially uniform focal spot profile intensity.

13. An apparatus comprising a laser beam converter as claimed in any one of the Claims 1 to 11 adapted so that in use that the target is placed slightly behind the focal plane of the principal focusing lens to achieve a substantially uniform focal spot profile intensity.

14. An apparatus as claimed in Claim 11 or Claim 12 characterised in that it is either a laser fusion apparatus, a laser heat processing apparatus, an apparatus for causing laser plasma interactions, or an apparatus for generating X-rays by laser illumination of a target.

15. A laser beam converter substantially as described above with reference to drawings 1, 2, 3, 4, and 9.

16. A laser beam converter substantially as described above with reference to drawings 1, 2, 3, 5, and 9.

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**Secti n 17 (The Search Report)** - 16 -

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GB 9309423.3

**Re..vant Technical fields**

(i) UK Cl (Edition L ) G2J (J33D)

(ii) Int Cl (Edition 5 ) G02B

**Databases** (see over)

(i) UK Patent Office

(ii) WPI

Search Examiner

R E HARDY

Date of Search

14 JUNE 1993

Documents considered relevant following a search in respect of claims ALL

| Category (see over) | Identity of document and relevant passages | Relevant to claim(s) |
|---|---|---|
| | NONE | |

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| Category | Identity of document and relevant passages | Relevant to claim(s) |
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